NBS SPECIAL PUBLICATION 393

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Colorimetry and Spectrophotometry: A Bibliography of NBS Publications January 1906 Through January 1973

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Institute for Computer Sciences and Technology, and the Office for Information Programs.

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Office of Standard Reference Data — Office of Information Activities — Office of Technical Publications — Library — Office of International Relations.

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
[2] Part of the Center for Radiation Research.
[3] Located at Boulder, Colorado 80302.
[4] Part of the Center for Building Technology.

Colorimetry and Spectrophotometry: A Bibliography of NBS Publications January 1906 Through January 1973

Kenneth L. Kelly

Building Environment Division
Center for Building Technology
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, *Secretary*
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

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COLORIMETRY AND SPECTROPHOTOMETRY: A BIBLIOGRAPHY OF NBS PUBLICATIONS JANUARY 1906 THROUGH JANUARY 1973

Kenneth L. Kelly

This bibliography of publications will serve as the key to the large amount of research into color measurement and specification, and color vision carried out by the staff of the National Bureau of Standards (NBS) in colorimetry and spectrophotometry. These 623 publications appeared in NBS publications and outside scientific and technical journals between January 1906 and January 1973. This material has been in constant demand by Bureau members as well as by outside individuals and organizations. The practical value of this wealth of information lies in its ready accessibility to the scientific and technical fraternity by title, by key words or by author, in the Library of Congress and in depository libraries such as large public and university libraries. A short organizational chronology of the colorimetry and spectrophotometry program is included.

Key Words: Bibliography; color; color codes; color measurement; colorimetry; spectrophotometry; vision.

1. INTRODUCTION

This paper lists the 623 publications on colorimetry[1] and spectrophotometry[2] authored by members of the staff of the National Bureau of Standards published during the years 1906 to 1973. (There were no relevant papers between 1901, the year the Bureau was founded, and 1906). This listing, made necessary by the constant demand for this information, also contains the publications of Research Associates and Guest Workers in these fields. In addition to the chronological list[3], it contains an Author[4] and a Subject Index[5]. The reference numbers appearing in these indexes refer to the entries in the chronological listing. A short organizational chronology of the colorimetry and spectrophotometry program is included.

2. HISTORY

Soon after the founding of the Bureau of Standards in 1901[6], studies in photometry and colorimetry were undertaken by members of the staff at the request of business, science and industry. The results of these studies appeared as papers in the Bulletin of the Bureau of Standards and in other scientific and technical journals. Among the projects undertaken in these formative years were those in the fields of length, electricity, spectroscopy, fibers

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[1] Colorimetry - the study of color measurement, specification, designation, tolerances, blindness, color-order systems, vision.

[2] Spectrophotometry - the spectral measurement of reflecting or transmitting samples, including reduction of the data.

[3] See Sections 9.

[4] See Section 11.

[5] See Section 10.

[6] Name changed from Bureau of Standards (BS) to the National Bureau of Standards (NBS) in 1934.

and clinical thermometers in addition to the work in photometry and colorimetry. The challenges to these "pioneers" were tremendous as shown by the diversity of fields studied by so few men. Standardization of colors was the field of research which attracted the most interest and concern in industry as well as in the scientific community [1][7]. Requests for assistance in color measurement and standardization were received from the fields of cottonseed oil, margarine, butter, from glass (in signal lamps, headlights and spectacles for eye protection), to petroleum oil, turpentine, rosin, paper and textiles, from flour, sugar, eggshells, egg yolks, dyes and water to chemical solutions, paints, portland cement, tobacco, to porcelain, enamels and even blood and human skin -- the latter of concern to biologists and anthropologists.

The list of authors of these papers reads like an early Who's Who in Science. Some of these men later rose through the ranks at the Bureau, while others went to scientific or industrial organizations where they carried on the high-level and imaginative research which characterized their early developmental years at the Bureau. Many of the early papers listed in this report formed the cornerstones of all photometry and colorimetry, such as the one on the standard visibility curve [2] by Gibson (1916)[8] and Tyndall (1919)[8], and the paper defining the International Commission on Illumination (ICI) (now Commission Internationale de l'Éclairage (CIE)) Standard Observer and Coordinate System [3] by Judd (1927)[8].

It can be seen from the chronological listing that the early colorimetry work was carried on by Hyde (1902)[8], Nutting (1903)[8] and Ives (1908)[8]; Nutting was in charge in 1911. In 1913 Mr. Irwin G. Priest (1907)[8] was Chief of the Section on Colorimetry in the Optics Division, and he continued in that capacity until his death in 1932, when he was followed as Chief by Dr. K. S. Gibson. In 1948 the Optics Division was merged with the Electricity Division to form the Division of Electricity and Optics, and by reorganization the Division of Optics and Metrology in 1950. In 1955, on Dr. Gibson's retirement, Mr. L. E. Barbrow became Chief of the Photometry and Colorimetry Section which in 1960 became part of the Metrology Division. In 1966 the Colorimetry and Spectrophotometry Section was reformed with Mr. I. Nimeroff as Chief. When the Metrology Division was combined with the Division of Atomic and Molecular Physics in 1969, the colorimetry program was transferred into the Institute for Applied Technology and designated as the Office of Colorimetry. The Spectrophotometry part of the old Colorimetry and Spectrophotometry Section became the Spectrophotometry Section of the new Optical Physics Division. Most of the Office of Colorimetry was transferred in 1970 to the Applied Acoustics and Illumination Section of the Building Research Division[9]. Now the colorimetry program is in the Sensory Environment Section of the Building Environment Division. Dr. Judd, one of the world authorities on color, remained with the colorimetry program until his death in 1972, although assigned as consultant to the Director of the Institute for Applied Technology. Despite the organizational changes identified above, significant work continued on color standards, tolerances, measurement, specification and color vision.

These changes reflect new demands from rapidly expanding fields of research. Among these, for instance, are challenging new problems arising from the fast growing fields of aerospace (heat balance between solar radiation and cold in space craft), color standards and tolerances (specify color and acceptable variation in purchase specifications) and safety (one safety color code for marking physical hazards and highway traffic signs, adapted to help color blind).

3. CONTRIBUTIONS FROM PRIVATE INDUSTRY

A considerable source of inspiration and support to the Colorimetry Section in its early days came from Mr. A. H. Munsell, a noted artist from Boston. Mr. Munsell realized that there was no practical and scientific method of teaching color either in art schools or in the grade schools where most students get their first color instruction. He worked toward the realization of "a simple and practical notation, or method of writing (designating)

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[7]Figures in brackets [] indicate the literature references in the Bibliography (Section 8).

[8]Year each joined the Bureau of Standards.

[9]Now the Center for Building Technology.

color" [4] by the use of a system that "portrays the three dimensions (hue, value or lightness and chroma or saturation) of color, and measures each by an appropriate scale" [5], each scale to consist of colored samples separated by visually equal steps. The clarifying phrases in parentheses are the author's.

Mr. Munsell's first contact with the Bureau of Standards was in 1901, just after the formation of the Bureau when he wrote Dr. Stratton, the Director, "asking about color" [6]. He visited the Bureau in 1911 where he met Dr. P. G. Nutting who was in charge of the work that included colorimetry. Mr. Munsell's son, Mr. A.E.O. Munsell, met Mr. Priest in 1921 and from this meeting a very close relationship developed from which the Colorimetry and Spectrophotometry Section has benefited materially throughout the years. An indication of the degree of cooperation, is the fact that the Munsell Color Company has placed seven Research Associates at the Bureau. By 1940, 23 papers covering this work had been presented to the Optical Society of America [7]. In addition, a good deal of unpublished work was performed which contributed "to the development of basic information necessary, if (the) Munsell (color-order system), or any other color system was to be critically studied or standardized" [8].

This work funded by the Munsell Research Laboratory was conducted both at NBS and at the Munsell Research Laboratory in Baltimore. In addition to the regular Munsell Color Company staff, seven persons were employed at one time or another in the strictly scientific work at the Baltimore Laboratory. These were: Miriam O'Brian, Louise Sloan (Rowland), Geraldine Walker (Haupt), employed by NBS in 1927, I. H. Godlove, Carl Boechner, Prentice Reeves and Willard Valentine. The seven Research Associates placed at NBS were: Casper L. Cottrell, I. G. Priest, D. B. Judd, F. H. Harris (retired later as Section Chief in the Electricity Division), F. G. Brickwedde (retired later as Division Chief of the Heat and Power Division), E.P.T. Tyndall and W. Greenberg.

A significant contribution of the Colorimetry and Spectrophotometry Section to the designation of color in art, science and industry came through research funded by the American Pharmaceutical Association. This work led to a simple, easily understood and accurately defined method of designating colors "in which the color-name boundaries were specified in Munsell notation" [9]. It also provided the impetus for many of the papers listed here, culminating with the Color Names Dictionary (NBS Circular 553) [10] published by the Inter-Society Color Council (ISCC) and the National Bureau of Standards (NBS) in 1955, the ISCC-NBS Centroid Color Charts (NBS Standard Sample #2106) [11] in 1965 and the Universal Color Language [12] in 1965. In addition, this research played a vital role in the formation of the Inter-Society Color Council (ISCC)[10] in 1931 and the Color Marketing Group (CMG)[11] in 1962.

The close cooperation between NBS and the Munsell Color Company has continued through the years. This has resulted in such landmark developments as the Munsell Renotation System in 1943, in which the spacings in the three scales of hue, value (lightness) and chroma (saturation) were smoothed and each color was specified in the 1931 CIE system, and facilitated Munsell's significant contribution to the development of the ISCC-NBS Centroid Colors in 1965. The Munsell Color Company in 1967 funded a cooperative study to develop an improved, visually uniform, color spacing technique based on the work of the Optical Society of America (OSA) Committee on Uniform Color Scales (1966).

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[10] The founding of the Inter-Society Color Council was a direct outgrowth of the early work on the color-names project. It exists as a medium for interchange of information and development of basic concepts on color-related problems.

[11] The Color Marketing Group was a direct outgrowth of the ISCC. Its purpose is the use of color to better market products and services at a profit.

In 1942, the Munsell Color Foundation was formed at the request of the members of the Munsell family. Two of the duties of this non-profit Foundation were to hold the stock of and assume the direction of the Munsell Color Company. A further indication of the continuing close cooperation between NBS and the Munsell Color Company was a stipulation in the formation of the Foundation, that one of the three original Trustees was to be appointed by the Director of NBS. Dr. Judd was so appointed, and was elected President of the Foundation by the other Trustees. He served as President without remuneration from its formation in 1942 until his death in 1972.

Many scientific and technical associations and companies have contributed to the work of the Colorimetry and Spectrophotometry Section, and in so doing, have benefited in return. The Corning Glass Works, for instance, through their Dr. H. P. Gage cooperated with our Dr. K. S. Gibson between 1926 and 1946 in the development and application of colored glass filters to be used as the color standards in railway signaling in this country. Before the development of spectrophotometry and the 1931 CIE Standard Observer and coordinate System [3] as the means of interpreting spectrophotometric data, standard limit glasses were used to control the range of color acceptable for a particular signal application. So successful was this system that it served as the basis of the signaling systems used later for the control of vehicular, marine and aircraft traffic. Only now is this system of colored glass standards being slowly supplanted by photoelectric colorimetry and spectroradiometry, a method by which the color of the whole signal device consisting of a lamp or kerosene flame, reflector and colored lens, can be measured in operating position.

4. IMPACT OF PUBLICATIONS

The papers listed here have had a considerable influence on the development and application of color in science, art and industry. The chronological listing including the Author and Subject Indexes is almost synonymous with the basic work in vision in the first three quarters of the 20th century. Researchers like Nutting, Tyndall, Priest, Gibson, Judd and Hunter (1927)[8] are among those who contributed greatly to the fields of vision as well as color. Judd's basic book on Color in Business, Science and Industry in its two editions, has been "the" textbook in color psychophysics[12] since its publication in 1952. Subjects like the visibility of radiant energy (now the luminous efficiency function), photometry of lamps, color vision, color blindness, color-order systems, the CIE Standard Observer and Coordinate System, spectrophotometry, color measurement and specification, safety color codes, gloss and other surface characteristics, color temperature, color standards and tolerances constitute only a partial listing of the contributions made by NBS to the development and application of color in commerce and industry.

5. COOPERATION WITH OUTSIDE ORGANIZATIONS

Throughout the years, the members of the Colorimetry and Spectrophotometry Section have contributed to and held positions of leadership in many scientific and technical organizations. In several they have been charter members. Among these are:

American Association for the Advancement of Science
American Ceramic Society
American Institute of Physics
American Instrument Society
American Medical Association
American Oil Chemists Society
American Pharmaceutical Association
American Physical Society
Astronomical Society
Association of Physics Teachers
Color Marketing Group
Illuminating Engineering Research Institute

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[12] Color Psychophysics is the study and application of psychophysical methods to the investigation and measurement of color.

Institute of Electrical Engineers
International Color Association
International Commission on Illumination
Inter-Society Color Council
London Illuminating Engineering Society
Munsell Color Foundation
Optical Society of America
Physical Society of London
Societie Francaise de Physique
Union of Geodesy and Geophysics
Washington Academy of Medicine
Washington Academy of Sciences

The members have also contributed to and held positions in a number of standardizing organizations, such as:

American Association of Textile Chemists and Colorists
American National Standards Institute (first the American Engineering Standards Committee, then the American Standards Association, then the United States of America Standards Institute)
American Society for Testing and Materials
Association of American Railroads
Electronic Industries Association
Illuminating Engineering Society
Institute of Traffic Engineers
International Standards Organization
National Education Association
National Joint Committee on Uniform Traffic Control Devices for Streets and Highways
Technical Association of the Pulp and Paper Industry
Textile Color Card Association (now the Color Association of the United States)

They have also worked closely with and contributed to programs dealing with color in a number of government agencies including:

Department of Agriculture
Department of Defense
Department of Transportation
Federal Aviation Administration
Federal Communications Commission
General Services Administration
National Academy of Sciences
National Research Council
Occupational Safety and Health Administration
Post Office Department
Veterans Administration

Another important contribution of the Colorimetry and Spectrophotometry Section throughout its more than a half-century of existence, has been the sharing of its expertise with those non-professionals as well as specialists seeking information on color and vision. Letters of inquiry and requests for assistance have come from all parts of the United States and cover a wide range of subjects. An indication of the diversity of the requests is provided by the following examples:

Tell me all about color
What colors were the circle and dot of the insignia on the allied planes in World War I?
What color is 31643?
Detailed requests about color vision
Requests for assistance in developing color standards and tolerances for the Federal Government or for industry
Requests for color assistance in books on photogrammetry, flowers, oceanography, mushrooms

Mortuary cosmetics
Skin colors

6. THE NUMBERING SYSTEM

The individual papers in this list have been arranged according to the year and month of publication. As stated earlier, each paper has been assigned a serial number starting with 1. These numbers are also used to reference individual papers under specific headings and under authors' names in the Author Index and in the Subject Index.

Each reference includes besides the chronological serial number, the author's name(s), the title of the paper or abstract, the abbreviation of the journal or publication in which it appears, the volume number underscored, the beginning page number and the year of publication in parentheses. If the paper is published in more than one journal, subsequent references follow the first and are separated by semicolons.

7. IN APPRECIATION

It is a pleasure to acknowledge the contributions of each of the members of the Colorimetry and Spectrophotometry Section, especially Dr. Deane B. Judd who sponsored this project, and who, with his very broad knowledge and experience, was a constant source of inspiration and guidance.

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3. Judd, Deane B., See item 221 in Section 9.

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5. Ibid, p. 42.

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7. See 4 above, p. 46.

8. Ibid, p. 47.

9. Ibid, p. 49; also see 6 above, p. 585.

10. Kelly, K. L. and Judd, D. B., See item 465a in Section 9.

11. See item 517a in Section 9.

12. Kelly, Kenneth L., see item 518 in Section 9.

9. CHRONOLOGICAL LIST OF PUBLICATIONS

1. Hyde, Edward P.
Talbot's law as applied to the rotating sectored disk.
Bull. Bur. Stand. 2, 1 (1906) S26.

2. Nutting, P. G.
A pocket spectrophotometer.
Bull. Bur. Stand. 2, 317 (1906) S39.

3. Nutting, P. G.
Purity and intensity of monochromatic light source.
Sci. Pap. Bur. Stand. 2, 439 (1907) S44.

4. Nutting, P. G.
The complete form of Fechner's law.
Bull. Bur. Stand. 3, 59 (1907) S49.

5. Nutting, P. G.
The luminous equivalent of radiation.
Sci. Pap. Bur. Stand. 5, 261 (1908) S103.

6. Nutting, P. G.
A method for constructing the natural scale of pure color.
Bull. Bur. Stand. 6, 89 (1909-10) S118.

7. Nutting, P. G.
Luminosity and temperature.
Bull. Bur. Stand. 6, 337 (1909-10) S103.

8. Ives, Herbert E.
Daylight efficiency of artificial illuminants.
Bull. Bur. Stand. 6, 231 (1909-10) S125.

9. Ives, Herbert E.
White light from the mercury arc and its complementary.
Bull. Bur. Stand. 6, 265 (1909-10) S128.

10. Nutting, P. G.
The visibility of radiation. A recalculation of Koenig's data.
Bull. Bur. Stand. 7, 235 (1911) S154.

11. Nutting, P. G.
A photometric attachment for spectroscopes.
Bull. Bur. Stand. 7, 239 (1911) S155.

12. Nutting, P. G.
A new precision colorimeter.
Bull. Bur. Stand. 9, 1 (1913) S187.

13. Priest, Irwin G.
Color specifications.
Rep. Proc. Fourth Ann. Meet. Soc. Cotton Products Analysts (now the Amer. Oil Chem. Soc.), p. 6, June 21, 1913.

14. Priest, Irwin G.
A photometric error sometimes accompanying the use of a pair of nicols, and a proposal for its elimination.
J. Wash. Acad. Sci. 3, 298 (1913).

15. Coblentz, W. W.
The diffuse reflecting power of various substances.
Bull. Bur. Stand. 9, 283 (1913) S196.

16. Priest, Irwin G.
The quartz colorimeter and its applicability to the color grading of cotton seed oil.
Rep. Proc. Fifth Ann. Meet. Soc. Cotton Products Analysts (now Amer. Oil Chem. Soc.) p. 21, May 16, 1914.

17. Priest, Irwin G.
A proposed method for the photometry of lights of different colors.
Phys. Rev. (2), 6, 64 (1915); 9, 341 (1917); 10, 208 (1917).

18. Priest, Irwin G.
The Bureau of Standards contrast method for measuring transparency.
Trans. Amer. Ceram. Soc. 17, 150 (1915).

19. Priest, Irwin G. and Peters, Chauncey G.
Report on investigations concerning the color and spectral transmission of cotton seed oil.
Report Proc. Sixth Ann. Conv. Soc. Cotton Products Analysts (now Amer. Oil Chem. Soc.), p. 67, May 14-15, 1915.

20. Priest, Irwin G.
A simple spectral colorimeter of the monochromatic type.
J. Wash. Acad. Sci. 6, 74 (1916).

21. Gibson, K. S.
The effect of temperature upon the coefficient of absorption of certain glasses of known composition.
Phys. Rev. N. S., 7, 194 (1916).

22. Middlekauf, G. W. and Skogland, J. F.
An interlaboratory photometric comparison of glass screens and of tungsten lamps, involving color differences.
Sci. Pap. Bur. Stand. 13, 287 (1916) S277.

23. Gibson, K. S.
The effect of temperature upon the absorption spectrum of a synthetic ruby.
Phys. Rev. N. S. 8, 38 (1916).

23a. Priest, I. G.
Specifications of the transparency of paper and tracing cloth.
BS Circ. No. 63 (May 1917).

24. Priest, Irwin G. and Peters, Chauncey G.
Measurement and specification of the physical factors which determine the saturation of certain tints of yellow.
Tech. Pap. Bur. Stand. No. 92 (1917) T92.

25. Howe, H. E. and Gibson, K. S.
The ultraviolet and visible absorption spectra of phenolphthalein, phenol-sulphonphthalein and some halogen derivatives.
Phys. Rev. N.S. 10, 767 (1917).

26. Crittenden, E. C. and Richtmyer, F. K.
An "average eye" for heterochromatic photometry, a comparison of a flicker and an equality-of-brightness photometer.
Bull. Bur. Stand. 14, 87 (1918-19) S299.

27. Coblentz, W. W. and Emerson, W. B.
Relative sensibility of the average eye to light of different colors and some practical applications to radiation problems.
Bull. Bur. Stand. 14, 167 (1918-19) S303.

28. Coblentz, W. W. and Emerson, W. B.
Luminous radiation from black body and the mechanical equivalent of light.
Sci. Pap. Bur. Stand. 14, 255 (1917) S305.

29. Priest, Irwin G.
The work of the National Bureau of Standards on the establishment of color standards and methods of color specification.
Trans. Illum. Eng. Soc. 13, 38 (1918).

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Discussion of Troland's paper "Psychology of Color".
Trans. Illum. Eng. Soc. 13, 21 (1918).
With special reference to determination of standard of white light. Trans. Illum. Eng. Soc. 13, 74 (1918).

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A precision method for producing artificial daylight.
Phys. Rev. (2), 11, 502 (1918).

33. Priest, Irwin G.
The law of symmetry of the visibility function.
Phys. Rev. (2), 11, 498 (1918).

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Spectroradiometric investigation of the transmission of various substances.
Bull. Bur. Stand. 14, 653 (1918-19) S325.

35. Gibson, K. S.
Photoelectric spectrophotometry by the null method.
Sci. Pap. Bur. Stand. 15, 325 (1919-1920) S349.

36. Priest, Irwin G.
A one-term pure exponential formula for the spectral distribution of radiant energy from a complete radiator.
J. Opt. Soc. Amer. 2-3, 18 (1919).

37. Coblentz, W. W. and Emerson, W. B.
Glasses for protecting the eyes from injurious radiations (3rd edition).
Tech. Pap. Bur. Stand. No. 93 (1919) T93.

38. Priest, Irwin G.
A new formula for the spectral distribution of energy from a complete radiator.
Phys. Rev. (2), 13, 314 (1919); 14, 191 (1919).

39. Gibson, K. S. and McNicholas, H. J.
The ultraviolet and visible transmission of eye-protective glasses.
Tech. Pap. Bur. Stand. No. 119 (1919) T119.

40. Priest, Irwin G. and Gibson, K. S.
Report on the applicability of ultra-violet rays to signaling.
Phys. Rev. (2), 14, 188 (1919).

41. Priest, Irwin G. and Tyndall, E.P.T.
Optical and photographic methods for the detection of invisible writing.
Phys. Rev. (2), 14, 188 (1919).

42. Priest, Irwin G.
A method for the color grading of red flares.
Phys. Rev. (2), 14, 264 (1919).

43. Priest, Irwin G., Meggers, W. F., McNicholas, H. J., Gibson, K. S. and Tyndall, E.P.T.
The spectral composition and color of certain high intensity searchlight arcs. (In cooperation with the Searchlight Investigation Section, Corps of Engineers, USA).
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16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

This bibliography of publications will serve as the key to the large amount of research into color measurement and specification, and color vision carried out by the staff of the National Bureau of Standards (NBS) in colorimetry and spectrophotometry. These 623 publications appeared in NBS publications and outside scientific and technical journals between January 1906 and January 1973. This material has been in constant demand by Bureau members as well as by outside individuals and organizations. The practical value of this wealth of information lies in its ready accessibility to the scientific and technical fraternity by title, by key words or by author, in the Library of Congress and in depository libraries such as large public and university libraries. A short organizational chronology of the colorimetry and spectrophotometry program is included.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

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